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Current Status and Future Research Opportunities for Electrochemical Capacitors: Relevance for Naval and Civilian Applications

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**CURRENT STATUS AND FUTURE RESEARCH OPPORTUNITIES
FOR ELECTROCHEMICAL CAPACITORS:
RELEVANCE FOR NAVAL AND CIVILIAN APPLICATIONS**

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Electrochemical capacitors (ECs) are a class of energy-storage devices that offer significant promise in bridging the performance gap that exists between the high power density derived from electrostatic capacitors and the high energy density of batteries. As such, ECs will ultimately enable technologies and applications, ranging from microelectronics to hybrid- and all-electric vehicle platforms, where current energy-storage devices are not sufficient. Further advances in EC performance and viability will require fundamental research investigations focused on the development of new materials for active electrodes and electrolytes, the design and synthesis of new multifunctional composite materials, and the development of new electrode and device architectures.

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Background and Current Status

Electrochemical capacitors (ECs, also referred to by the trade names “supercapacitor” or “ultracapacitor”) are a class of energy-storage devices whose characteristics fill the large performance gap that exists between the high power densities offered by conventional capacitors and the high energy densities of batteries (see Fig. 1), while sharing certain features of both capacitors and batteries.^{12,3,4} For example, ECs typically exhibit sloping charge–discharge profiles that are reminiscent of

electrostatic capacitors, but are distinguished from electrostatic capacitors by their significantly higher energy densities ($>3 \text{ Wh kg}^{-1}$) and much lower operating voltages (typically $<5 \text{ V}$ per cell). From both a practical and a fundamental perspective, ECs are more closely related to batteries, and in fact, the distinction between these two classes of energy-storage devices has been blurred

with the recent introduction of “high-rate” batteries. However, ECs are commonly differentiated from high-rate batteries by charge–discharge response times that are <10 seconds. The sloping charge–discharge profiles of ECs result in lower energy densities relative to conventional batteries, but also provide an important benefit as an indication of the state-of-charge of EC cells as they are electrochemically cycled. Long lifetimes and low maintenance are another key advantage of ECs when compared to current battery technologies.

The term “electrochemical capacitor” actually describes a diverse class of devices that incorporate a variety of active materials (high-surface-area carbons, electroactive polymers, and transition metal oxides), electrolytes (conventional aqueous and nonaqueous electrolytes, advanced polymer electrolytes and ionic liquids), and device configurations (symmetric and asymmetric). Such device diversity and design flexibility is an important advantage of ECs, and explains the broad region on the power vs. energy density spectrum that can be addressed by current EC technology. In order to understand the trade-offs and benefits associated with specific EC configurations, it is important to first define the two principal charge-storage

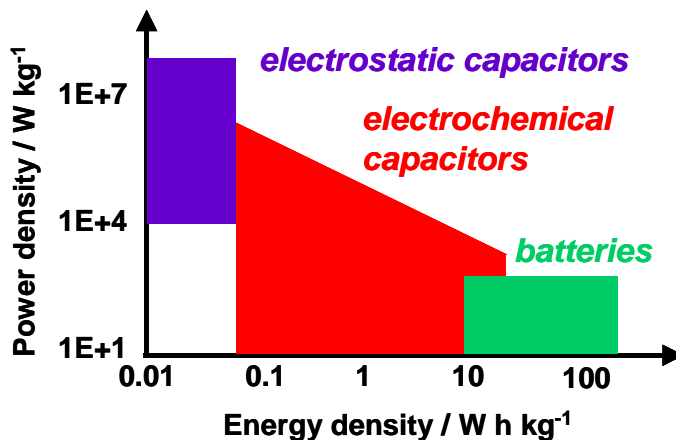


Figure 1. Diagram of approximate power and energy density ranges of current battery and capacitor energy-storage technologies.

mechanisms that are encountered with ECs: (i) double-layer capacitance, and (ii) pseudocapacitance.

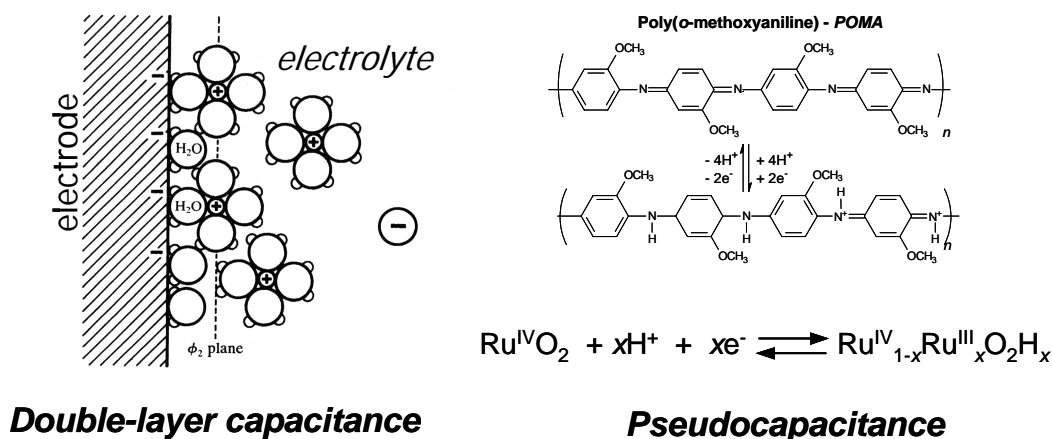


Figure 2. Examples of double-layer capacitance (left) and pseudocapacitance (right) charge-storage mechanisms.

Double-layer capacitance arises due to the charge separation that occurs at all electrode/electrolyte interfaces, resulting in area-normalized capacitances on the order of 10–50 $\mu\text{F cm}^{-2}$. Because double-layer capacitance is an interfacial phenomenon, increased energy density is realized by using high-surface-area electrodes. Therefore, electrical double-layer capacitors (EDLCs) are constructed using a variety of porous, high-surface-area carbons^{5,6,7} including activated carbon, nanotubes/nanofibers, and aerogels, where specific capacitances of up to 250 F g^{-1} can be achieved. Specific capacitance is only one parameter that influences the performance of the resulting EDLC. For example, the energy density of a symmetric EDLC is defined by the equation, $E = 1/8 CV^2$, where C is the specific capacitance of an individual electrode and V is the operating voltage of the two-electrode cell.¹ To maximize energy and take advantage of the square dependency of the voltage term, commercial EDLCs⁸ typically use electrolytes based on acetonitrile or organic carbonates, which provide operative voltages of ~3 V. Although commercial EDLCs with acetonitrile-based electrolytes exhibit energy densities (3–5 Wh kg^{-1}) that are competitive for certain niche applications and technologies, the broader application of EDLCs is currently hampered by their high cost per unit of energy density relative to conventional batteries, and issues associated with the cost and safety of acetonitrile electrolytes. Ionic liquids are an alternative class of electrolytes that also exhibit large operating voltage windows, but are distinguished from conventional nonaqueous electrolytes by their low

volatility.⁹ Japan Radio recently commercialized an EDLC with an ionic liquid electrolyte, which is rated at 3 V and delivers a power density of 13.5 kW L^{-1} .¹⁰ However, ionic liquids have yet to gain widespread acceptance for use with ECs due to their relatively high cost and modest ionic conductivity.

The term “pseudocapacitance” describes rapid and reversible faradaic reactions whose sloping discharge profiles mimic those of double-layer capacitors. Because this mechanism involves electron-transfer reactions and is not strictly limited to the electrode/electrolyte interface, materials exhibiting pseudocapacitance typically provide higher energy densities than double-layer capacitors, although the kinetics of pseudocapacitance reactions can be significantly slower than for the double-layer process. The pseudocapacitance phenomenon is observed for a wide range of electroactive materials, including transition metal oxides, conductive nitrides, and conducting polymers. The underlying faradaic mechanisms of pseudocapacitance are closely related to those of conventional battery materials, and in fact, certain battery materials, such as V_2O_5 , exhibit pseudocapacitance when prepared in high-surface-area forms.¹¹ Disordered, hydrous forms of nanoscale RuO_2 are considered state-of-the-art amongst pseudocapacitive materials, exhibiting specific capacitances as high as 720 F g^{-1} ,¹² facilitated by a cation–electron insertion mechanism in acidic aqueous electrolytes (see Fig. 2). Ruthenium oxides also possess anomalously high electronic conductivity ($>1 \text{ S cm}^{-1}$), which facilitates high power densities in ECs that utilize this oxide. Unfortunately, the high cost of ruthenium, a platinum-group metal, has stifled the application of ruthenium oxides for present or future large-scale commercialization. Alternative lower-cost oxides, including nickel and manganese oxides are currently being investigated, but to date, none have exhibited performance comparable to hydrous RuO_2 .

Conducting and redox polymers are another potential alternative to hydrous RuO_2 for EC applications, and have been explored as such for more than a decade.^{13,14} Conducting polymers can be prepared by either electrochemical or chemical methods from such monomers as aniline, pyrrole, thiophene, and their derivatives. The redox mechanisms for conducting polymers are somewhat more complex than for metal oxides, but also involve coupled ion–electron exchange reactions, resulting in specific capacitances ranging from $100\text{--}500 \text{ F g}^{-1}$. The most intriguing property of certain conducting polymers, such as poly-3-(4-fluorophenyl)thiophene, PFPT, is the ability to undergo both p-doping and n-doping. Thus the same polymer could be used as either

the cathode or anode in an EC device.¹⁵ Rudge et al. demonstrated that capacitors using PFPT as the active electrode material produced energy densities approaching 39 Wh kg^{-1} (normalized to the active material mass) and cell voltages $>3 \text{ V}$. The primary disadvantages of conducting polymers for ECs is their variable conductivity as a function of charge-state, which limits practical film thickness for electrodes composed only of the conducting polymer, and long-term stability problems due to mechanical stresses that arise within the polymer structures during electrochemical cycling.

Double-layer capacitance and pseudocapacitance charge-storage mechanisms are complementary in the sense that the former is ideal for high power needs while the latter provides significantly higher energy density. This realization has resulted in a relatively new class of electrochemical capacitors based on asymmetric configurations that utilize a double-layer capacitance material in one electrode and a faradaic material in the opposing electrode.¹⁶ By carefully matching the two types of electrode material one can achieve devices that exhibit much higher energy densities than symmetric EDLCs, while maintaining rapid charge–discharge properties. The most common asymmetric capacitor configurations use a faradaic metal oxide cathode, such as PbO_2 or Ni(OH)_2 , and an activated carbon double-layer anode, in conjunction with an aqueous electrolyte (either H_2SO_4 or KOH). Because of the high overpotential of the carbon anode for the hydrogen evolution reaction, cell voltages of $1.5\text{--}2.2 \text{ V}$ can be achieved, far beyond the normal voltage window for aqueous electrolytes ($\sim 1.2 \text{ V}$). This extension of the operating voltage range mitigates the one disadvantage of aqueous electrolytes, which otherwise are preferred to nonaqueous electrolytes due to their low cost, low flammability, high ionic conductivity, high electrolyte solubility, and less rigorous cell packaging requirements. Zheng reported that the maximum theoretical energy density of a $\text{Ni(OH)}_2\|\text{KOH}\|\text{carbon}$ asymmetric capacitor as 40 Wh kg^{-1} ,¹⁷ an energy density that simply cannot be achieved with present EDLCs. Asymmetric ECs of this type are commercially available from ESMA¹⁸ in Russia, although their products are not optimized for high-rate operation. Nickel oxides provide high capacity as a cathode material, but have the disadvantages of relatively high cost and toxicity.

Due to the diversity of both material components and device design, asymmetric electrochemical capacitors present an opportunity to address a wide range of energy/power requirements. Recent research efforts have focused on the development of manganese oxides

as an alternative cathode material in asymmetric ECs that use mild aqueous electrolytes.¹⁹ Amatucci and co-workers have adapted asymmetric EC design concepts to cells that use nanostructured $\text{Li}_4\text{Ti}_5\text{O}_{12}$ as a faradaic anode and activated carbon as a combination double-layer/intercalation cathode, in conjunction with nonaqueous electrolytes to produce packaged cells with energy densities $> 20 \text{ Wh kg}^{-1}$.²⁰

Basic Science Challenges and Opportunities for Electrochemical Capacitors

To date, investment and interest in electrochemical capacitor development has been dwarfed by the research and development efforts in batteries, particularly considering the recent focus on lithium-ion batteries (see for example the Department of Energy's *Freedom Car* program).²¹ As new technologies have emerged, with their increasingly demanding power requirements, there is now a renewed interest in ECs, either as stand-alone energy-storage devices for high-power needs, or alternatively for hybrid EC–battery systems that can address both power and energy requirements. Although the performance of current ECs is sufficient for certain applications, the full potential of ECs, particularly in terms of energy density, has yet to be realized. Future advances in EC technology will require a concentrated research effort that addresses both basic and applied research issues. A focused basic research effort on the design and production of new materials and electrode architectures will ultimately result in technologically relevant ECs with energy densities $>15 \text{ Wh kg}^{-1}$ and $>25 \text{ Wh L}^{-1}$, response times of $< 10 \text{ s}$, increased cycle life at high voltage and temperatures, and in economically competitive forms.

New directions for EC research at the basic research level are outlined in the proceeding sections. These recommendations are based on information collected by the author from the April 2007 DOE Workshop, “Basic Research Needs for Electrical Energy Storage,”²² from internet resources,²³ and from a survey of the recent scientific literature. For organizational purposes, these recommendations are divided into four general categories: (i) nanostructured, ultraporous carbons for EDLCs; (ii) redox-active materials for enhanced energy density via pseudocapacitance; (iii) multifunctional composites and architectures; and (iv) electrolytes. There are also many cross-cutting issues that impact some or all of these four research directions. For example, the development and adaptation of theory and modeling to EC capacitor systems, a topic not addressed in detail in this report, will be required to design new EC materials and

structures and to understand fundamental processes that support optimized performance in operational ECs.

(i) Designing Nanostructured, Ultraporous Carbons for Enhanced EDLC Performance

The electrochemical performance of symmetric EDLCs is largely determined by the physical structure of the high-surface-area carbons that comprise the active electrode materials. Because double-layer capacitance is an interfacial phenomenon, one would nominally design an EDLC electrode with the smallest possible pores (micropores, defined as having pore diameters < 2 nm), to achieve the highest surface area within a given volume. Carbons with extensive microporosity, such as activated carbon, yield the highest specific capacitance. Unfortunately, the capacitance contribution of electrified interfaces within micropores typically declines at high rates, due to double-layer overlap, ion-sieving effects, poor electrolyte wetting, and hindered ion transport.^{24,25} Initially reported by Soffer and Koresh in 1977, this general phenomenon has been verified for an extensive range of microporous carbons over the last 30 years. Some recent work has now challenged the established connection between pore size and capacitance. Using carbide-derived carbons with well-defined microporous structures, Gogotsi and co-workers reported an anomalous increase in area-normalized capacitance as the pore size approaches the dimensions of an unsolvated electrolyte ion.²⁶ The high capacitance observed in sub-nanometer pores was attributed to the close proximity of unsolvated electrolyte ions to the electrified carbon surface. At present these effects have been observed only with specific carbide-derived carbons, which are far too expensive for commercial applications. The ability to rapidly charge and discharge the carbon/electrolyte interface in such small pores also remains a point of contention.

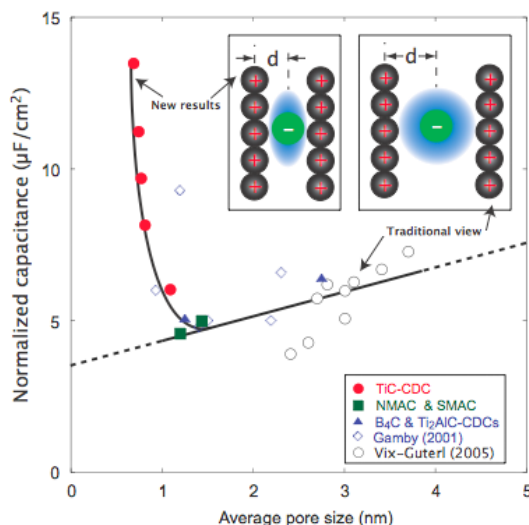


Figure 3. Area-normalized capacitance as a function of pore size for microporous carbide-derived carbons (Chmiola et al., *Science* **313**, 1760 (2006)).

These recent results do highlight the need, however, to re-examine the fundamental relationships between pore size and electrochemical performance, particularly for very small

pores. Our present double-layer charging theories are inadequate to explain sub-nanoscale effects that could be operating in such materials, including the thermodynamics of the ion solvation–desolvation events, and possible electronic density redistribution at the carbon surface. New carbon materials²⁷ with well-defined pore structures will be required as a platform for these fundamental studies. With a more rigorous understanding of the interplay between pore size, double-layer capacitance, and charge–discharge kinetics, new carbon materials should be designed and produced with “engineered” pore structures to achieve specific energy and power density targets for EDLC performance.

Carbon nanotubes (CNTs) have achieved notoriety for a host of energy-related possibilities due to their high electronic conductivity, chemical stability and relatively high specific surface areas.²⁸ The ability to fabricate CNTs in relatively dense, aligned architectures may ultimately promote high power density via optimized ion-transport pathways.²⁹ Despite such promise, the reported specific capacitance values for a wide variety of single-walled and multi-walled CNTs rarely exceed 120 F g^{-1} , which is barely competitive with low-cost activated carbons. The relatively modest specific capacitance of native CNTs can be ascribed to the low area-normalized double-layer capacitance of the basal-plane carbon surfaces³⁰ that comprise the CNT walls. “Bamboo-type” CNTs,³¹ which have exposed edge-plan graphite walls, should also be explored as active materials for ECs, because the double-layer capacitance of the edge-plane surface is 3–4 times greater than for the basal plane surface. The modification of the CNT walls with specific oxygen and/or nitrogen functionalities will provide additional charge-storage capacity via pseudocapacitance reactions. Even with significant improvements in performance, the future implementation of CNTs for commercialized devices will require substantial reduction in production costs as well as increased production volume.

The anomalous charge-storage behavior of high-surface-area carbon anodes in aqueous asymmetric capacitors is a special case where basic research investigations are warranted. As described above, the asymmetric design delivers energy densities that far exceed those possible with EDLCs, and allows the use of low-cost, safe, and highly conductive aqueous electrolytes. The increased energy density of the asymmetric design arises not only from the capacity of the redox-active metal oxide cathode, but also from pseudocapitance mechanisms at the carbon anode. The additional specific capacitance that is realized when carbon is charged at progressively negative voltages (see Fig. 4) has been attributed to the electrochemical

adsorption/desorption of hydrogen atoms on the carbon surface from the contacting aqueous electrolyte.³² Because the additional charge accumulation and release occurs at more negative potentials (i.e., higher cell voltages in a two-electrode device), the energy density gains from this pseudocapacitance process are even more pronounced. To further exploit this phenomenon for high-performance asymmetric ECs, the underlying mechanisms of this pseudocapacitance process, and their relation to the chemical and physical properties of various nanostructured carbon materials should be investigated.

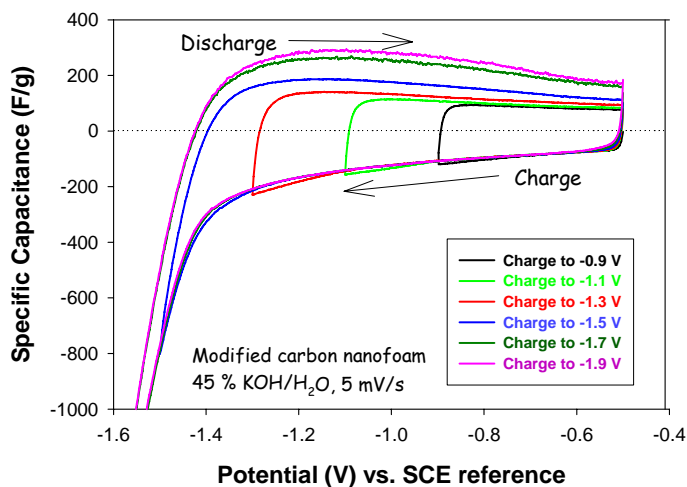


Figure 4. Cyclic voltammograms showing the charge-discharge behavior of a modified carbon nanofoam electrode as it is charged progressively to more negative potentials (unpublished data, J.W. Long, Naval Research Laboratory, 2007).

(ii) Exploiting Redox-Active Materials for Enhanced Energy Density via Pseudocapacitance

The extension of ECs to new applications is hampered by the relatively low energy densities of current EC technology, based primarily on EDLCs. To compete with ever-improving high-rate batteries, new EC technology must move beyond EDLCs and incorporate redox-active materials as components of one or both electrode structures. The outstanding electrochemical performance of hydrous RuO_2 in ECs sets a challenging benchmark for pseudocapacitance materials, although its high costs are prohibitive for all but the most specialized applications. The development of new low-cost, high-performance materials will be a critical step in realizing high energy density ECs, and should include both inorganic and polymeric materials, and also extend to previously unexplored classes of materials. Manganese and iron oxides are promising low-cost alternatives,^{33,34,35} but to date their electrochemical performance falls short of that for hydrous RuO_2 . Further research should be devoted to optimizing the electrochemical performance and long-term stability of such low-cost oxides. Conductive nitrides have recently been proposed for EC applications, with nanoscale vanadium nitrides exhibiting specific capacitances of up to 1300 F g^{-1} .³⁶ Polyoxymetalates are another

class of redox-active inorganic materials that may be beneficial for ECs,³⁷ although research with polyoxometalates is currently focused on their catalytic properties. Judging from a survey of the recent literature, the interest in conducting polymers as stand-alone electrode materials for ECs has declined considerably, but may be revived where conducting polymers are used in composites with other redox-active materials.³⁷

The fundamental mechanisms of pseudocapacitance reactions are still being investigated, and because the pseudocapacitance phenomenon is exhibited by a broad class of materials, the operational mechanisms of particular materials, often based on complex and specific redox reactions, cannot be generalized to new materials as they are discovered. Charge-storage mechanisms may also be affected by the introduction of advanced electrolyte compositions. Ultimately, revolutionary advances in energy and power storage densities in ECs that rely on pseudocapacitance for charge-storage will emerge from a stronger fundamental understanding of the underlying mechanisms. Established spectroscopic methods (e.g., X-ray absorption spectroscopy) that are compatible with in-situ investigations should be exploited to further characterize the pseudocapacitance process.

The properties of all electrochemical systems strongly depend on interfacial phenomena, and pseudocapacitor materials and structures are no exception. Future fundamental research efforts must focus on understanding the interactions that occur at the interfaces between the active pseudocapacitor material and contacting electrolyte. The findings of such studies should be used to design materials that exhibit more robust and functional interfaces. For example, Naoi et al. recently demonstrated that thin conducting polymer coatings could enhance the proton-electron exchange at the surfaces of RuO_2 nanoparticles (see Fig. 5), resulting in a five orders of magnitude enhancement in the electrochemical cycle lifetime.³⁸ Related approaches should be explored to enhance the performance and stability of

other redox-active materials. Surface and interface design strategies should also be directed at

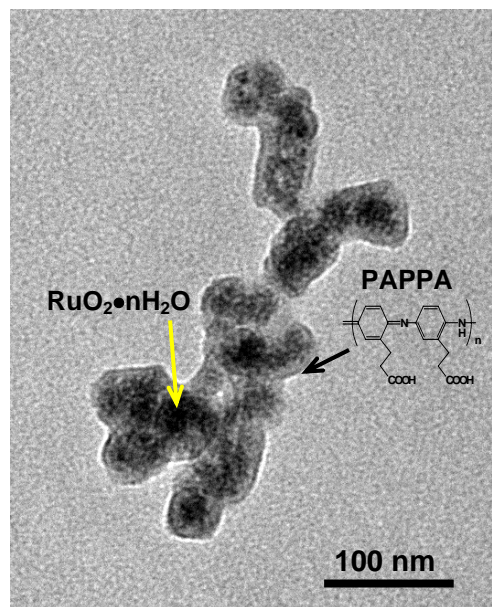


Figure 5. Nanoscale hydrous RuO_2 coated with thin layers of the conducting polymer, PAPP (K. Machida et al., *Electrochemistry* **72**, 404 (2004)).

coatings that promote self-healing or self-regulation of the redox potential. A fundamental understanding of interfacial phenomena, including charge-storage processes, will also be critical to achieve stability and high performance for pseudocapacitor materials.

(iii) Multifunctional Composites and Architectures—Bringing it all together

The components of an electrode structure must serve a variety of distinct and often divergent functions: (i) electron conduction; (ii) ion conduction; (iii) charge-storage; and (iv) defining the physical pore-solid structure of the electrode itself. Few individual materials exhibit all of these properties. Therefore, new composite materials and architectures will be required, in which selected components are assembled into a multifunctional structure. For example, ultraporous carbon nanoarchitectures (nanotube assemblies or aerogels/nanofoams) may serve as the conductive 3-D scaffolding for composite architectures onto which redox-active materials are incorporated. In such a configuration, the carbon nanostructure bears the burden of long-range electronic conduction, while the redox-active component provides energy-storage capacity via pseudocapacitance mechanisms. When properly designed and fabricated, multifunctional composite architectures of this type will deliver optimized combinations of both energy and power density. Distributing the redox-active component as a nanoscale coating may also relieve mechanical stresses that arise during the charge-discharge process. Early examples of such multifunctional architectures included conducting polymers on the surfaces of high surface area carbon nanotubes³⁹ or aerogels⁴⁰ coated with thin layers of conducting polymers. More recently this design concept has been extended to include nanoscale manganese oxides on nanostructured carbons.^{41,42}

(iv) Electrolytes – Addressing Issues of Voltage, Conductivity, Stability and Cost

The performance of electrochemical capacitors in terms of theoretical energy and power density is typically dictated by the properties of the active electrode materials, but in practice device performance metrics and lifetime may be limited by properties of the electrolyte. An ideal electrolyte would exhibit: (i) high ionic conductivity; (ii) excellent chemical and electrochemical stability; (iii) a wide operating voltage window, particularly when used for EDLCs; (iv) low volatility and low flammability; (iv) the ability to exhibit the characteristics above over a wide temperature range (-30°C to 100°C); (v) low toxicity and production from renewable and sustainable methods; and (iv) low cost. Achieving all of these attributes in a

given electrolyte is a difficult challenge. Conventional nonaqueous electrolytes (based on acetonitrile and organic carbonates) facilitate high operating voltages, but suffer from issues of high flammability, low ionic conductivity, and limited electrolyte solubility. Aqueous electrolytes offer a low-cost alternative with high ionic conductivity and solubility, but have a limited voltage range (a limitation somewhat mitigated in the asymmetric aqueous capacitor design). Ionic liquids are being investigated as replacements for traditional nonaqueous EC electrolytes due to their low volatility and low flammability,^{9,43,44} but their use is limited by their relatively low ionic conductivity and high cost.

Many of the same electrolyte requirements described above also apply for batteries, and thus, advances in bulk electrolyte performance will benefit both battery and EC technology. Electrochemical capacitors, however, present an additional challenge for electrolyte design, due to the nanostructured, high-surface-area character of the EC electrode structures, where interfacial electrode/electrolyte interactions and confinement effects are more critical. Advancements in EC electrolyte performance will only proceed from a more thorough and fundamental understanding of electrode/electrolyte interactions in functional EC materials and structures. As described earlier, the relative sizes of electrolyte ions and the pores of the electrode structure are one factor that determines the capacitance and charge–discharge kinetics of EDLCs, but even this relationship is still poorly understood. Ionic liquids may provide an ideal model system for investigating these questions, as they are “neat” electrolytes with no additional solvent.⁴⁵ The dynamics of electrolyte structure in nanometer and sub-nanometer pores should be thoroughly investigated using a variety of spectroscopic methods (dielectric, Raman, electron paramagnetic resonance, etc.) and other structure-probing techniques (e.g., X-ray and neutron scattering), particularly those that are compatible with *in-situ* studies. The interactions of electrolytes with redox-active materials that exhibit pseudocapacitance should be investigated. Electrolytes must also be designed to promote fast charge transfer at the electrode/electrolyte interface, and to maximize the chemical and electrochemical stability of the active high-surface-area electrode material.

Near- and Long-Term Impact of Electrochemical Capacitors for Military and Civilian Applications

The development and commercialization of electrochemical capacitor technology is still in its infancy compared to battery technology, but the long cycle life and high-rate charge–discharge capabilities of ECs are already being exploited or investigated for a wide range of commercial and applications, including:⁴⁶

Telecommunications → high-power backup energy storage for portable and stationary applications

Power generation/distribution → energy storage and leveling; particularly advantageous for renewable energy sources with intermittent generation

Industrial → meeting peak power demands and peak shaving for a variety of industrial applications; hybrid-electric power trains for industrial equipment

Transportation → high-power energy storage/delivery for hybrid-electric and all-electric vehicle platforms

Consumer electronics → providing high power density and long lifetime for portable electronics.

Perhaps the most visible technology that will be impacted by electrochemical capacitors is hybrid–electric and all–electric vehicles. The high-rate charge–discharge capabilities of ECs are particularly advantageous for hybrid–electric vehicle power trains, where energy is captured from regenerative braking and subsequently released through electric motors that assist vehicle acceleration and reduce the burden on the internal combustion engine. To date the use of ECs for hybrid–electric applications has been directed at large vehicle platforms that operate in a frequent start–stop mode, for example the Flyer-ISE gasoline hybrid bus (see Fig. 6) that is currently being used in several southern California cities.⁴⁷



Figure 6. A Flyer-ISE gasoline hybrid 40' bus (see http://www.isecorp.com/ise_products_services/gasoline_hybrid_drive_system/).

The benefits of hybrid–electric technologies are also being exploited for military applications. The Oshkosh Truck Corporation is currently developing the diesel–electric hybrid,



Figure 7. An Oshkosh HEMTT A3 with ProPulse® diesel–electric hybrid vehicle (<http://www.oshkoshtruckcorporation.com/news/media-center~defense.cfm>).

Heavy Expanded Mobility Tactical Truck (HEMTT) for the U.S. Army (see Fig. 7), which delivers fuel economy increases of up to 20% relative to the non-hybrid equivalent. This particular hybrid uses only electrochemical capacitors to meet its energy-storage requirements.⁴⁸ Improving the fuel efficiency of combat vehicles and platforms will significantly reduce the logistics burden of fuel distribution in hostile environments.

Hybrid–electric systems are not only beneficial for vehicles, but are also applicable to a number of stationary industrial platforms, particularly those that operate with repetitive motions. One specific example is the hybrid–electric cargo transfer crane (see Fig. 8), initially developed in Japan, but now being implemented in ports around the world. Conventional cranes are powered directly by diesel engines. By adding a hybrid–electric system that includes ECs and/or batteries, it is possible to recapture a significant fraction of the energy expended in lifting loads. With this design a smaller diesel engine can be used as a generator for the hybrid system, greatly reducing fuel consumption and air pollution in the surrounding environment.



Figure 8. A hybrid–electric cargo transfer crane (<http://www.greencarcongress.com/2006/08/hybridelectric.html>).

The long cycle life and low maintenance needs of electrochemical capacitors are ideal properties for applications that require energy storage in remote locations. One such example is the Waverider buoy from Datawell PV, which is used to measure and report wave motion at various remote sites in the ocean (see Fig. 9).⁴⁹ The primary energy source for the Waverider is a collection of solar panels. The intermittent output of the solar panels is bridged by a hybrid energy-storage system comprising primary batteries and Maxwell's BOOSTCAP[®] ultracapacitors.⁵⁰ The ultracapacitors provide the necessary overnight energy storage during summer months when the daytime solar panel output is high, while the primary battery bank provides much of the energy over the winter months. The use of electrochemical capacitors in such a hybrid system reduces the demands on the battery, and significantly lengthens the time between required maintenance visits.

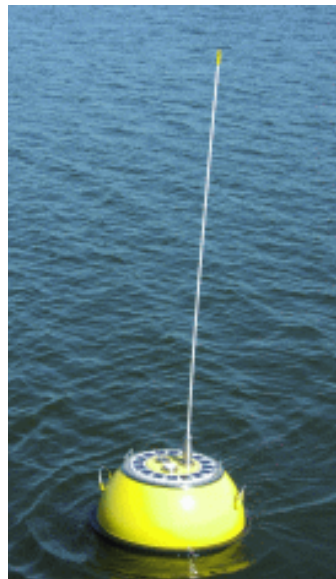


Figure 9. A Waverider buoy
(<http://www.rsaquaco.uk/products/waves.asp>).

The examples cited above represent only a sampling of applications where ECs are and will be an enabling technology.

Summary

Electrochemical capacitors are a promising class of energy-storage devices that can address the power/energy needs of current-generation and emerging applications. To ensure continued advancements in EC performance, basic research programs focusing on new materials development, new electrode and device architectures, and on fundamental investigations of the underlying charge-storage and -transport mechanisms will be essential. The development of advanced EC technology will ultimately enable the deployment of technologies that cannot be supported by current-generation energy-storage devices.

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